Magnitude and Value of Electric Vehicle Emissions Reductions for Six Driving Cycles in Four U.S. Cities with Varying Air Quality Problems

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ABSTRACT

The emissions of logically competing mid-1990 gasoline vehicles (GVs) and electric vehicles (EVs) are estimated as if the vehicles were driven in the same pattern (driving cycle). Six different driving cycles are evaluated, ranging in speed from 7 to 49 miles per hour (mph). These cycles are repeated using specific fuel composition, electric power mix, and environmental conditions applicable to Chicago, Denver, Los Angeles, and New York. The year 2000 emissions differences are estimated for each of five pollutants: HC, CO, NO_x, and SO_x, and CO_2. With use of EVs, HC and CO emissions are consistently lowered by 98% or more.

Across metropolitan areas, CO_2 emissions reductions are uniformly large at low speed, but variable at high speed. It is found that initially-introduced EVs could achieve 100% emission reductions in Chicago by using off-peak power from nuclear power plants for recharging EVs. Emissions reductions occur for all combinations in Los Angeles and for most combinations in New York, except for SO_x. NO_x emissions are reduced in all four cities.

An "avoided cost" value in dollars per ton of emissions reductions for each of the five pollutants is estimated in each of the four cities. The values for each city depend on severity of air quality standard violations. Dollar value of EV emissions reductions is calculated with dollars per ton of emissions reductions and estimated emissions reductions by EVs over the vehicle lifetime. The emissions reduction value is estimated as if a mid-1990s EV is substituted for a GV for each driving cycle in each city. Depending on driving conditions assumed, the emissions reduction value for EVs driven an average of 1.6 hours per day (h/d) ranges from \$12,600 to \$19,200 in Los Angeles; \$8,500 to \$12,200 in New York; \$3,200 to \$9,400 in Chicago; and \$6,000 to \$9,000 in Denver (1989\$).

INTRODUCTION

Use of electric vehicles (EVs) is considered to be an effective strategy to reduce vehicular air pollutant emissions. Since 1989, several studies have been conducted to compare air pollutant emissions between EVs and comparable gasoline-powered vehicles (GVs) *(1-6)*. Accounting for power-plant emissions increases due to EV use, these studies show large reductions in per-mile vehicle emissions of hydrocarbons (HC) and carbon monoxide (CO) by EVs relative to GV emissions. EV use could decrease or increase emissions of nitrogen oxides (NO_x), depending on the type of power plants that provide electricity for recharging EVs and the intensity of NO_x emission control in the power plants. EV use usually increases emissions of sulfur oxides (SO_x) and particulate matter (PM), primarily because SO_x and PM emissions from GVs are small. To bring about the emissions reduction benefits of EVs, the California Air Resources Board (CARB) has mandated the sale of EVs by vehicle manufacturers after 1997 *(7)*. States in the Northeast region of the United States are likely to follow California's mandate of EV sales.

In analyzing EV emission impacts, all previous EV studies used the GV emissions that were estimated with the driving conditions specified in the U.S. federal urban driving schedule (FUDS). In reality, because of the limited range of EVs and traffic congestion in the major urban areas where EVs are most likely to be used, most early model EVs are likely to be driven at speeds lower on average than those simulated by FUDS-specified conditions. The per-mile GV emissions that are to be eliminated by use of such EVs tend to increase significantly as average driving speed decreases. For example, the U.S. Environmental Protection Agency's

(EPA's) Mobile5A model estimates that GV emissions at 5 miles per hour (mph) are two or three times more than those at the FUDS average speed (19.6 mph) *(8)*.

Although EV electricity consumption rates (kilowatt-hours per mile) and emission rates (grams per mile) also differ under different driving conditions, they are far more stable than for GVs. To analyze the effects of driving conditions on EV emission impacts, this study estimated GV emissions and EV electricity consumption (therefore EV emissions) under six driving cycles ranging in average speed from 7 to 49 mph and compared EV emissions with GV emissions under each of the six cycles (Table 1).

Estimated emissions of GVs can differ from state to state, since federal or state legislation/regulation allows different measures to control motor vehicle emissions. Currently, California has different emissions certification standards than the rest of the nation and uses its own emissions model called EMFAC. In the future, the Northeast states may adopt California's certification standards. On-road emissions rates, as estimated by models, also vary because of different ambient environmental factors. For EVs, the mix of power-plant types providing electricity differs in different regions, and so do the emission control efforts in power plants. In summary, EV emissions at any given speed show far more geographical variation than do emissions of GVs, while GV emissions in any given metropolitan area show far more variation in per-mile emissions rates as a function of driving speed than EVs.

Previous EV studies have focused on the significant regional variation in EV emissions but have ignored the significant speed variation of EV and GV emissions. Although two studies *(2, 4)* have compared EV emission impacts in different U.S. regions, they analyzed regional EV emissions for large regions (for example, Wang et al.'s study analyzed EV impacts in California and in the United States, and ICF's study divided the U.S. into ten regions and analyzed EV emission impacts for each region). This study selected four major U.S. metropolitan areas--Chicago, Denver, Los Angeles, and New York-- and analyzed EV emission impacts for each individual area.

A recent study by Ford that examined emissions reduction potential in the Los Angeles basin estimated a dollar value for the predicted emissions reductions by EVs *(9)*. For the Los Angeles area, Ford estimated a cumulative value of nearly $9,000 for avoided emissions control costs made possible by introduction of an average household EV. Our estimates are more comprehensive than Ford's. We estimate EV emissions reduction values for four cities under various driving speeds. We use Mobile5A to estimate on-road GV emissions, while Ford used GV emissions standards. Because of this, we estimate larger dollar values for Los Angeles than did Ford. We also estimate larger values for Los Angeles than elsewhere. It should be noted that the costs paid for emission control in the Los Angeles basin are the highest in the United States. The value of EV emissions reductions in Los Angeles should be greater due to both the severity of violations of individual air quality standards and the number of the pollutants for which standards are violated. Since the mechanism driving emitters to pay to reduce emissions is the violation of ambient air quality standards, payments for further control can only be expected for those pollutants contributing to violations (although payments for further control of emissions where pollutant concentrations marginally meet the standard can also be expected). Thus, the locations that can be expected to pay most for EVs or be most likely to force EV introduction through regulations will have violations of ambient air quality standards (e.g., ozone and/or CO standards).

METHODOLOGY

This study used a comparative approach to analyze EV emission impacts relative to GV emissions. The emission comparison was conducted under each of the six driving cycles (Table 1) and in four metropolitan areas (Chicago, Denver, Los Angeles, and New York). Among the four areas, Chicago violates the federal ozone standard; Denver violates the federal CO standard; Los Angeles violates the federal ozone, CO, and NO_x standards; and New York violates the federal ozone and CO standards. The analysis was targeted to a base year of 2000, although the substitute EV and GV were assumed to be 1996 vehicle models. Emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x),and carbon dioxide (CO_2) were analyzed. Emissions of other pollutants such as particulate matter and toxic air pollutants were not included in this study.

Calculation of GV Emission Rates

On-road per-mile GV emissions of HC, CO, and NO_x were calculated with Mobile5A, the most recent version of EPA's Mobile model for estimating on-road vehicle emissions. To account for emission deterioration effects, GVs were assumed to have about 50,000 miles accumulated. This implies that a GV with 50,000 miles accumulated in the year 2000 is actually produced around 1996. Mobile5A was run to generate GV emissions for the average speed of each of the six driving cycles and with ambient temperature, gasoline Reid vapor pressure (RVP), and inspection and maintenance (I/M) program applicable for each metro area. The stage

II technology to control vehicle refueling emissions at gasoline service stations was assumed to be implemented in Chicago, Los Angeles, and New York, where the federal ozone standard is violated. When calculating emissions of HC and NO_x, we used summertime (July) temperature, but when calculating emissions of CO, we used wintertime (January) temperature. This is because HC and NO_x emissions contribute to formation of ozone, whose concentrations peak on hot summer days, while CO emissions and ambient concentrations peak on cold winter days. This approach is recommended by the U.S. EPA for estimating motor vehicle emissions inventories.

GV emissions of SO_x and CO_2 were calculated for different driving cycles with the following two formulas:

$$SO_x = 2{,}798 \times 0.03\% \times 64/32/MPG \quad (1)$$

$$CO_2 = (2{,}798 \times 86.6\%/MPG - CO \times 12/28) \times 44/12 \quad (2)$$

where

SO_x = SO_x (mainly SO_2) emissions in grams per mile

CO_2 = CO_2 emissions in grams per mile

2,798 = gasoline density in grams per gallon

0.03% = sulfur content of gasoline by weight (see Reference 2)

86.6% = carbon content of gasoline

MPG = vehicle fuel economy (miles per gallon; the estimation will be shown below)

CO = CO emissions in grams per mile (calculated with Mobile5A)

64 = molecular weight of SO_2

32 = molecular weight of sulfur

12 = molecular weight of carbon

28 = molecular weight of CO

44 = molecular weight of CO_2.

GV fuel economy under each of the six cycles was calculated by use of an on-road fuel economy profile vs. speed developed by Toyota *(11)*. The base SFUDS fuel economy is about 26 mpg, an on-road value representative of published city mpg values of manual-transmission-equipped 1993 subcompact cars *(12)*. Estimated MPG (and therefore SO_x and CO_2 emissions) vary with different driving cycles, but is the same for the four cities. Table 1 presents estimated GV MPG for each cycle.

Emissions from refining the crude to gasoline were included in estimating GV emissions. DeLuchi et al. *(13)* estimate refinery emissions of 0.85, 1.26, 1.46, and 1.99 grams per gallon of gasoline produced for HC, CO, NO_x, and SO_x, respectively. DeLuchi *(14)* estimates refinery emissions of 1,461 grams per gallon of gasoline produced for CO_2. Grams-per-gallon refinery emissions were assumed to be the same in the four cities. Grams-per-mile refinery emissions were calculated by dividing the grams-per-gallon emissions by GV fuel economy.

Calculation of EV Emissions

Unless augmented with fuel-using auxiliary heat or power sources, EVs themselves do not produce emissions, but power plants that provide electricity for EVs do. The emissions comparison between EVs and GVs here is the comparison between the power-plant emissions attributable to EV use and the vehicle and refinery emissions attributable to GV use. No auxiliary EV power sources are included nor are estimates of electricity demand for heating and cooling of the EV. Emissions of EV battery recycling could be a potential concern. However, we estimated that NO_x emissions of EV lead-acid battery recycling are at about 0.0017-0.0034 grams per mile, or less than 1% of per-mile GV NO_x emissions.

The value of the gram-per-mile EV emissions is equal to the power-plant emission rate in grams per kilowatt-hour of electricity generated times the EV electricity consumption rate in kilowatt-hours per mile. The average power-plant emission rates for EV recharging were calculated from the emission rates and the percentage of EV electricity generated by power-plant types.

The effect of driving cycle on EV electricity consumption was estimated using a computer model. Marr and Walsh of Argonne National Laboratory (ANL) have established a micro-computer software package called MARVEL to model EV electricity consumption rates under different driving cycles *(15)*. Taking into account vehicle rolling resistance, drag resistance, EV powertrain efficiency, battery and charger efficiency, and other factors, MARVEL simulates the dynamics of vehicle movement and generates per-mile electricity consumption of EVs. Dr. Marr has run MARVEL for this study to generate EV electricity consumption rates for each of the six driving cycles. Input values were characteristic of a projected sodium-sulfur battery-equipped, 2-4 passenger EV with weight and battery-pack size/weight characteristics similar to those of of the Ford Ecostar EV.

Integration of Emissions with Estimates of Dollar Values per Ton

Finally, per-mile GV emissions were compared with per-mile EV emissions to estimate total emissions reductions per EV in tons. This estimate was based on an assumed average daily period of operation (1.6 hours per day [h/d]) held constant for each of the six driving cycles in each of the four cities. Dollar values per ton of emissions reductions (avoided costs that would otherwise have been incurred by other sources) were approximated using California Energy Commission's (CEC's) dollars-per-ton emissions values and EPA information on status of air quality standard violations *(16, 17)* . The reduced emissions in tons per vehicle and the dollar value estimates per ton were multiplied together for each pollutant in each metro area and for each driving cycle. Total values of emissions reduction per EV were developed for each metro area and under each driving cycle by adding the individual pollutant values.

RESULTS

GV Emission Rates

Per-mile GV emissions for HC, CO, NO_x, SO_x, and CO_2 calculated with the methodology described above are presented in Table 2. Grams-per-mile refinery emissions of HC, CO, NO_x, SO_x, and CO_2 are a function of driving cycle (i.e., gallons per mile) but do not vary by metro area. For example, under the SFUDS, refinery emissions are 0.033, 0.048, 0.056, 0.076, and 56 grams per mile for HC, CO, NO_x, SO_x, and CO_2, respectively.

EV Emission Rates

Power-Plant Emission Rates for EV Recharging

A given mix of power plants generates electricity to meet electricity demand in an individual region. When EVs are introduced, the EV electricity demand will be met by those types of power plants available to provide additional power. It is these so-called marginal plants that need to be considered in estimating EV emissions. The marginal plant mix for each of the four cities is presented in Table 3. Using the marginal mix and the emission rates of power-plant types (coal-, gas-, and oil-fired power plants), the average emission rates for EV recharging in each of the four cities were calculated and are presented in Table 4.

EV Emission Rates in Grams per Mile

To allocate power-plant emission rates in grams per kilowatt-hour of electricity to EV emission rates in grams per mile, EV electricity consumption in kilowatt-hours per mile is needed. Dr. Marr of Argonne National Laboratory ran the MARVEL computer model for this project to generate EV electricity consumption for each of the six driving cycles. The estimated EV electricity consumption rates are presented in Table 1. Marr's estimates are for a 2,750-lb-inertia weight EV assumed to be capable of carrying four passengers and using a projected sodium-sulfur (or equivalent) battery pack. To run MARVEL, these energy efficiencies were assumed: 85% for drivetrain efficiency, 85% for electric motor efficiency, 80% for battery efficiency, and 90% for battery charger efficiency.

The EV electricity consumption presented in Table 1 is at the wall outlet. To calculate EV emission rates using power-plant emission rates, the electric distribution and transmission loss, which amounts to about 8%, needs to be considered *(18)*.

EV Emission Impacts

The changes in per-mile passenger-car emissions due to EV use are presented in Figure 1. The figure presents EV emissions reductions on a percentage basis for each pollutant, under each driving cycle, in each of the four cities. Since it was assumed that nuclear-power plants will supply electricity for EVs in the Chicago area, EV emissions reductions are 100% in the Chicago area for each individual pollutant under each cycle (secondary uranium mining and processing emissions were not included in this study). Emissions reductions in the other three metropolitan (metro) areas are summarized below.

EV use reduces HC and CO emissions by over 98%, regardless of driving cycle or metro area. Use of EVs appears to be a technically effective strategy to help solve the CO air pollution problem in Denver, Los Angeles, and New York, and to help reduce the ozone air pollution problem in the areas where HC control will help reduce ozone formation.

The power plant mix in Los Angeles results in emissions reductions for all pollutants under the six driving cycles. Thus, in the area where across-the-board emissions reductions are most necessary -- in Los Angeles -- the estimated reductions are consistent and significant. Los Angeles is in an airshed that may be described as VOC/NO_x lean (smaller ratio of volatile organic compounds [VOCs] to NO_x) *(19)*. In the VOC/NO_x-lean areas, where control of HC (the predominant class of VOC) helps reduce ozone formation, use of EVs alleviates the ozone pollution problem. New York City is an area where HC reduction is predicted to be effective in reducing ozone, while NO_x reduction is not. However, NO_x reduction within the city should reduce downwind metro area ozone formation *(19)*. Thus, theory suggests that the Los Angeles and New York metro areas can benefit from simultaneous reductions of HC and NO_x. Houston is a city where HC reduction would not be very effective.

NO_x emissions in Denver, Los Angeles, and New York are reduced under each driving cycle. NO_x emissions reductions are about 10-40% in Denver, over 90% in Los Angeles, and about 80% in New York. In all three cities, the largest percentage NO_x emission reductions occur at the lowest speed, and emissions reductions decrease from the NYCC to the SAE D but increase again under the HWY. Overall, the reductions in both HC and NO_x by EVs will help solve the ozone air pollution problem in Los Angeles and New York. NO_x emission reductions will also help Los Angeles meet the federal ambient NO_2 standard.

For SO_x emissions, we have estimated that increases would occur in the absence of additional control. However, national SO_x emissions are capped and increases caused by EVs would have to be offset. SO_x emissions in Denver increase when using EVs under all driving cycles except the NYCC, and increase in New York under all six cycles. This is primarily because a large portion of EV electricity in these two cities is provided by coal- and oil-fired powerplants. SO_x increases in New York are much larger than in Denver. Though the percentage increases in SO_x emissions are large, the absolute amount of SO_x increase by EVs will be small compared to overall SO_x emissions because of the very tiny amount of SO_x emissions by GVs. The dollar value computations in the next section show that SO_x emissions are relatively unimportant. In Los Angeles, EVs reduce SO_x emissions by over 85%.

CO_2 emissions are decreased in Los Angeles and New York under each of the six cycles. The CO_2 percent changes in these two cities are from a reduction of 70% for the NYCC to approximately no change at the two highest speeds. In Denver, CO_2 emissions are reduced from 70% to 30% from the NYCC to the SFUDS, but increased by about 5% under the SAE D and the HWY. At higher average driving speeds, it appears that the effect of substituting EVs for GVs could be positive or negative depending on the estimate of relative fuel economy of the vehicles. For lower speeds, however, the estimation of a benefit for EVs is definite.

In the above analysis, the calculated EV emissions include the emissions of power plants located in and out of each of the metropolitan areas. The estimated refinery emissions of GVs may be in or out of the metropolitan areas. Since emissions of out-of-area power plants do not contribute to the emissions in each of the areas, actual air quality benefits of using EVs in each of the areas are likely to be larger than when the same emissions reductions are obtained by substituting low-emission, internal combustion engine vehicles for GVs. This is especially true for HC, CO, and NO_x, which cause area-confined air pollution problems. Since SO_x and CO_2 cause acid rain and global warming, which are regional or global pollution problems, the location of power plants is less critical to SO_x and CO_2 emissions.

Value of Emissions Reductions

A prior study by Ford for Southern California Edison of the dollar value of emissions reductions of EVs in Los Angeles driven according to the FUDS emissions test procedure arrived at an estimate of value per vehicle of about $9,000 in 1989 dollars *(9)*. In this study, we have assumed that one EV replaces one GV with exactly the same driving pattern over time. The vehicles last 13 years and are driven an average of 1.6 h/d, which is equivalent to 10,500 miles per year for the 18.5 mph SFUDS driving cycle. The annual mileage (and hours per day) are greater early in the vehicle's lifetime, tapering off in later years. Consistent with the California Energy Commission (CEC) methods of converting future costs into present value dollars, we convert our tons saved per year estimates to "present value" tons using a real discount rate of 4.0% *(20)*.

The value of the emissions reductions on a dollars per ton basis for Los Angeles was directly from the CEC (16). The value for the metro areas outside California was estimated by relating the avoided cost of emissions in various areas of California to the severity of the air quality violation there (see Table 5). If one of our non-California cities had the same level of air quality violation as a location in California, a dollars per ton value comparable to the California value was used. In the case of CO, the severity of violations in Denver and New York were intermediate between values in Los Angeles and the two other major California cities (i.e., San Diego and San Francisco). Thus, an intermediate dollars per ton value was selected. When no violation of a standard occurred, the corresponding emissions reductions were valued at zero. This is consistent with the CEC's control cost estimates (Reference *20*, Table 2).

The treatment of SO_x was different, primarily because we were attempting to make conservative assumptions that would not overstate the emissions reduction value of an EV. In the case of SO_x, it was assumed that costs would be incurred to offset emissions that would otherwise occur due to added electricity output caused by EVs. These costs would allow utilities to stay within the required SO_x cap.

It could be argued that the pollutants to which we have assigned a zero emissions reduction value should also be given a positive value in an area if maintenance of air quality related to that pollutant is marginal. For Chicago, whose ozone violations fall in the "extreme or severe" category, the average of the two dollars-per-ton values from the California "extreme or severe" cases was selected. The dollars-per-ton estimates for Chicago, Denver, and New York are obviously approximations, but they provide reasonably logical benchmarks.

Although emissions estimates have been presented in terms of grams per mile of driving, some reflection caused us to switch to a computation of dollar value of emissions reductions benefits based on typical hours of driving at the assumed average speed. A distance of 30 miles per day (mi/d) (equivalent to 11,000 miles/year) takes over four hours if the average speed is at the NYCC speed of 7.1 mph. It seemed highly unlikely that private owners would spend that many hours in a vehicle for commuting, shopping, and entertainment. Since 30 mi/d would take about 1.6 hours at the SFUDS speed, we assumed that the car would be on the road about 1.6 h/d on average.

The emission value estimates (Table 6) are not fully comparable to Ford's estimates because Ford did not include emissions from power plants providing EV power. If it had been estimated that some power plants are outside of the airshed, higher emissions reductions estimates would have resulted (except for Chicago). The GV emission estimates used in our study are consistently higher than those used by Ford, because we estimated on-road emissions and included refinery, evaporative, refueling, resting, and running loss emissions. The emissions reduction benefit estimate for Los Angeles with the SFUDS cycle, at about $18,200 per vehicle, is about twice Ford's estimate. The highest values for 1.6 h/d of driving occur at the highest speeds for Chicago, Los Angeles, and New York, and at the SAE C speed in

Denver. In general, HC and NO_x values peak at the HWY cycle--the highest speed, while CO values peak at the SAE C or SFUDS cycle--an intermediate speed.

The estimates for New York and Los Angeles provide an indication of the relative value of EVs in altering the emissions of motor vehicles. The value of reducing CO is estimated to be far greater than the value of reducing ozone precursors (HC and NO_x). Generally, the changes in SO_x and CO_2 emissions have a relatively small effect on the total avoided costs of emissions changes.

In summary, depending on driving conditions assumed, it is estimated that the emissions reduction value of EVs driven an average of 1.6 h/d in ranges from $12,600 to $19,200 in Los Angeles; $8,500 to $12,200 in New York; $3,200 to $9,400 in Chicago; and $6,000 to $9,000 in Denver (1989$).

In closing this section, we note that the method of avoided cost results in a much larger value of emissions reduction than would use of estimated avoided damage arising from the emissions reductions (based on California damage values recommended by National Economic Research Associates *(21)* and estimated by the CEC *(16, 22)*. The intention in this paper has been to get an idea what EVs are worth in terms of reduction of administratively imposed costs of complying with emissions standards. For those whose preferred method of valuation is damage estimates, we note that the CEC-recommended dollars per ton damage estimates (Reference *16*, Table 4.1) would result in an estimate that the emissions reduction value of EVs driven an average of 1.6 h/d in Los Angeles ranges from $720 to $3,500. However, for administrators within agencies charged with meeting the air quality goals that have been chosen through a national political process rather than an economic process, it is probably necessary to use control cost estimates to determine least-cost methods of meeting these goals.

CONCLUSIONS

This study shows that use of EVs reduces per-mile vehicle emissions of HC and CO by over 98% in four cities and under six driving cycles. The impacts of EV use on NO_x emissions depend on the stringency of NO_x emission control in power plants and types of power plants that provide electricity for EVs. In Chicago, Los Angeles, and New York, EV use helps significantly reduce NO_x emissions, with the greatest reduction occurring in Chicago. EV use causes moderate NO_x emissions reductions in Denver. The computation in this study illustrates that changes in SO_x emissions are large in percentage terms but are relatively unimportant in dollar value. EV use reduces CO_2 emissions sharply for trips with lower speeds (e.g., 20 mph or less) in cities other than Chicago and reduces it at all speeds in Chicago. However, like SO_x, the CO_2 emissions reductions are relatively unimportant in dollar value.

The analytical results from this study imply that use of EVs would be most valuable in addressing the CO air pollution problem in metropolitan areas such as Denver, Los Angeles, and New York. The use of EVs helps alleviate the ozone pollution problem, but the estimates indicate that the emissions control costs that can be avoided when EVs are used for this purpose is generally far smaller than for CO reduction. Costs of SO_x control should have little effect on the desirability of using EVs either for CO or ozone reduction. Relative to probable initial vehicle cost, the estimated values of emissions reductions are large if one assumes that the EVs are used by private owners driving about 1.6 h/d.

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DISCLAIMER

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TABLE 1 AVERAGE SPEED, GV FUEL ECONOMY, AND EV ELECTRICITY CONSUMPTION UNDER SIX DRIVE CYCLES

Driving Cycle[a]	Average Speed (mph)	GV Fuel Economy (MPG)	EV Electricity Consump. (Kwh/mi.)
NYCC	7.1	9.5	0.40
ECE-15	11.7	16.9	0.32
SAE C	15.4	21.3	0.35
SFUDS	18.5	26.1	0.37
SAE D	28.4	35.1	0.41
HWY	48.6	36.1	0.39

[a] For specifications of most of the driving cycles, see Reference 10. NYCC--New York city cycle; ECE-15--Economic Community of Europe Cycle 15; SAE C--SAE C cycle; SFUDS--simplified federal urban driving schedule; SAE D--SAE D cycle; HWY--highway cycle.

TABLE 2 GV EMISSIONS BY DRIVING CYCLE (GRAMS PER MILE)[a]

Pollutant	Chicago	Denver	Los Angeles	New York
NYCC:				
HC[b]	2.18	2.17	1.75	2.37
CO[c]	33.35	32.38	22.41	31.97
NO_x[c]	0.94	0.93	0.92	0.95
SO_x[c]	0.39	0.39	0.39	0.39
CO_2[c]	1030	1038	1054	1040
ECE-15:				
HC[b]	1.56	1.60	1.06	1.70
CO[c]	25.31	23.18	16.04	21.89
NO_x[c]	0.82	0.81	0.80	0.82
SO_x[c]	0.22	0.22	0.22	0.22
CO_2[c]	573	576	587	578
SAE C:				
HC[b]	1.29	1.35	1.07	1.39
CO[c]	21.59	22.90	13.68	19.52
NO_x[c]	0.78	0.77	0.76	0.78
SO_x[c]	0.17	0.17	0.17	0.17
CO_2[c]	452	450	464	455
SFUDS:				
HC[b]	1.11	1.20	0.95	1.19
CO[c]	19.62	17.97	12.44	17.74
NO_x[c]	0.76	0.75	0.74	0.76
SO_x[c]	0.14	0.14	0.14	0.14
CO_2[c]	366	368	377	369
SAE D:				
HC[b]	0.80	0.89	0.68	0.85
CO[c]	12.00	10.98	7.60	10.85
NO_x[c]	0.77	0.76	0.75	0.77
SO_x[c]	0.11	0.11	0.11	0.11
CO_2[c]	276	278	283	278
HWY:				
HC[b]	0.52	0.63	0.45	0.55
CO[c]	5.63	5.15	3.57	5.09
NO_x[c]	0.81	0.80	0.79	0.81
SO_x[c]	0.10	0.10	0.10	0.10
CO_2[c]	278	279	281	279

[a] These are emission rates for a 1996 model-year passenger car in year 2000.

[b] HC emissions include exhaust, evaporative (hot soak and diurnal), refueling, running losses, resting losses, and refinery emissions.

[c] Emissions of CO, NO_x, SO_x, and CO_2 include vehicular exhaust emissions and gasoline refinery emissions.

TABLE 3 MARGINAL POWER-PLANT MIX FOR EV RECHARGING (%)

Fuel Type	Chicago	Denver	Los Angeles	New York
Coal	0.0	52.6	7.5	24.0
Gas	0.0	35.2	85.0	28.0
Oil	0.0	3.3	0.0	48.0
Others[a]	100.0	8.9	7.5	0.0

[a] Including nuclear, hydropower, and other sources. It is assumed here that power plants fueled by these sources have zero air emissions.

TABLE 4 AVERAGE EMISSION RATES FOR EV RECHARGING (GRAMS PER KWH)

Pollutant	Chicago[a]	Denver[a]	Los Angeles[b]	New York[c]
HC	0.0	0.013	0.067	0.013
CO	0.0	0.123	0.087	0.150
NO_x	0.0	1.484	0.156	0.400
SO_x	0.0	0.714	0.029	3.900
CO_2	0.0	687	623	643

[a] Average emission rates were calculated from the rates of coal-, gas-, and oil-fired plants weighted by their mix. The marginal power-plant mix is presented in Table 3.

[b] The average emission rates for Los Angeles were calculated from the emission rates of coal- and gas-fired plants weighted by their mix. The marginal power-plant mix is presented in Table 3.

[c] The average emission rates for New York were calculated by Tennis (6) from the emission rates of power-plant types and their mix.

TABLE 5 ESTIMATED AVOIDED COSTS OF EMISSIONS REDUCTION (1989$/TON) AND SELECTED EMISSION VIOLATION STATUS

Pollutant	Chicago[a]	Denver[a]	New York[a]	Los Angeles[b]	San Diego[b]	San Francisco[b]
Ozone Violation Status	Extreme or Severe	In Attainment	Extreme or Severe	Extreme or Severe	Extreme or Severe	Moderate
HC	18,200	0	18,200	18,900	17,500	10,200
NO_x	22,350	0	22,350	26,400	18,300	10,400
CO Violation Status	In Attainment	High Moderate > 12.7 ppm	High Moderate > 12.7 ppm	Serious	Low Moderate ≤12.7 ppm	Low Moderate ≤12.7 ppm
CO	0	3,925	3,925	9,300	1,100	2,200
SO_x[c]	3,000	3,000	3,000	19,800	3,600	8,900
CO_2[d]	8.50	8.50	8.50	8.50	8.50	8.50

[a] These HC, NO_x, and CO values are ad hoc estimates judgmentally correlating CEC estimates (16) with the seriousness of violation (17) in the three California cities. CEC presented avoided costs in emission reductions in dollars/ton/year (20). By checking original data sources from which CEC derived its cost estimates, CEC's adjustment on cost estimates, and CEC's application of its cost estimates, we determine that CEC's estimates are actually in dollars/ton.

[b] Estimates based on CEC data (Reference 16, Table 4-1).

[c] Outside California, the lowest in-state control costs of CEC's estimates (16) are used (i.e., $3000 per ton).

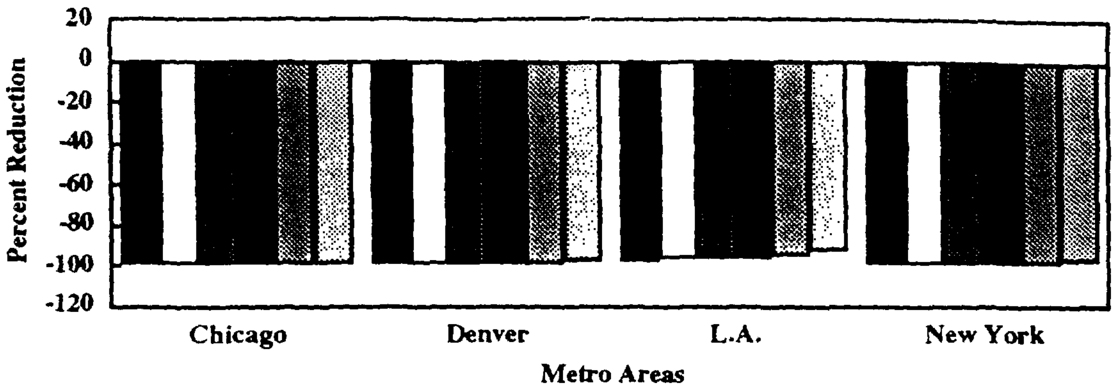
[d] CEC proposes use of $28 per ton of carbon, which is equivalent to $8.50 per ton of CO_2.

TABLE 6 ESTIMATED VALUE OF EV EMISSIONS REDUCTIONS (DOLLARS PER VEHICLE)[a]

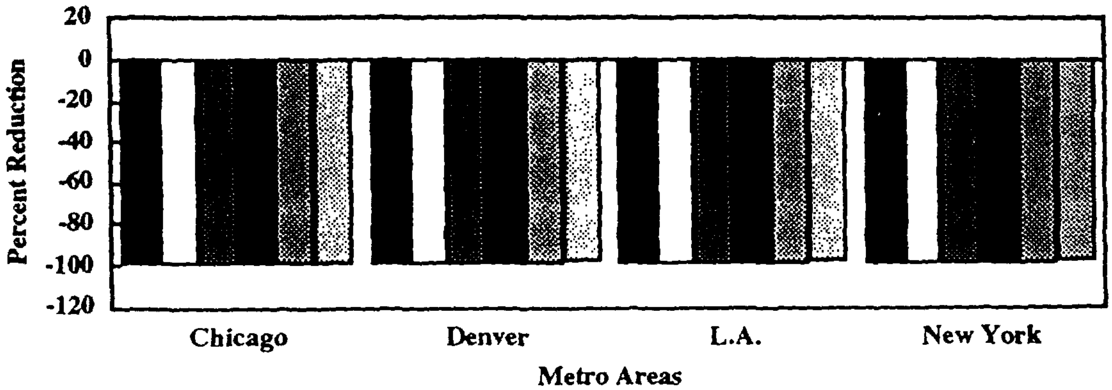
Driving Cycle Pollutant	Chicago	Denver	Los Angeles	New York
NYCC:				
HC	1,800	0	1,475	1,952
CO	0	5,756	9,439	5,681
NO_x	953	0	1,020	787
SO_x	53	10	336	-178
CO_2	399	285	302	293
Sum	**3,205**	**6,051**	**12,572**	**8,535**
ECE-15:				
HC	2,122	0	1,465	2,307
CO	0	6,789	11,131	6,408
NO_x	1,370	0	1,472	1,138
SO_x	49	-7	306	-256
CO_2	364	214	235	225
Sum	**3,905**	**6,996**	**14,607**	**9,822**
SAE C:				
HC	2,310	0	1,943	2,481
CO	0	8,826	12,488	7,517
NO_x	1,715	0	1,820	1,381
SO_x	51	-29	314	-387
CO_2	378	158	190	176
Sum	**4,455**	**8,955**	**16,755**	**11,098**
SFUDS:				
HC	2,383	0	2,062	2,549
CO	0	8,314	13,637	8,203
NO_x	2,008	0	2,113	1,582
SO_x	50	-52	303	-506
CO_2	368	92	127	111
Sum	**4,814**	**8,354**	**18,242**	**11,939**

<u>SAE D:</u>				
HC	2,642	0	2,230	2,788
CO	0	7,781	12,760	7,680
NO_x	3,123	0	3,260	2,400
SO_x	57	-116	331	-889
CO_2	426	-43	8	-13
Sum	**6,248**	**7,622**	**18,589**	**11,967**
<u>HWY:</u>				
HC	2,939	0	2,475	3,078
CO	0	6,213	10,203	6,126
NO_x	5,622	0	5,935	4,444
SO_x	95	-187	551	-1,445
CO_2	734	-32	44	17
Sum	**9,390**	**5,994**	**19,208**	**12,220**

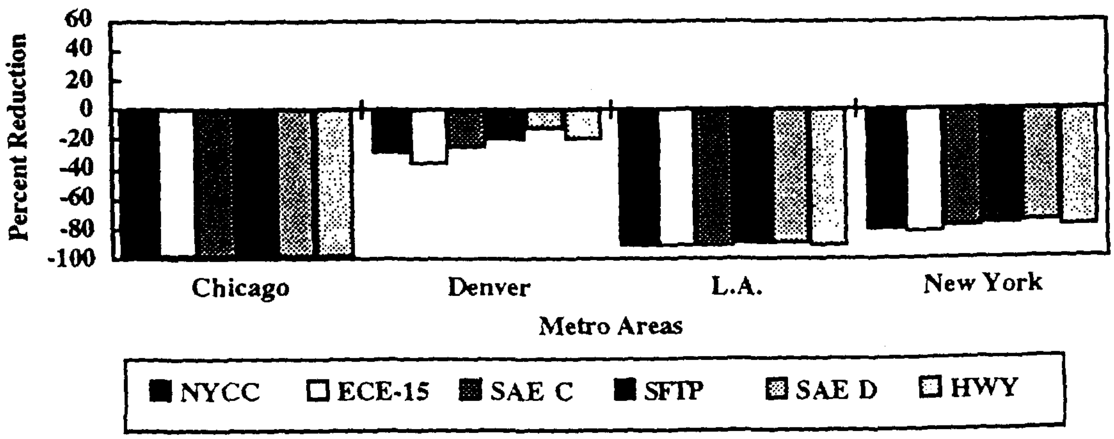
[a] EV driven 1.6 hours per day on the specified driving cycle, lasting 13 years, and experiencing greatest rate of use early in the vehicle life. These lead to different lifetime VMT (vehicle miles traveled) for different driving cycles. Specifically, EV lifetime VMT is 52,463 for the NYCC, 86,454 for the ECE-15, 113,794 for the SAE C, 136,700 for the SFUDS, 209,853 for the SAE D, and 359,115 for the HWY.



(a) Hydrocarbons (HC)

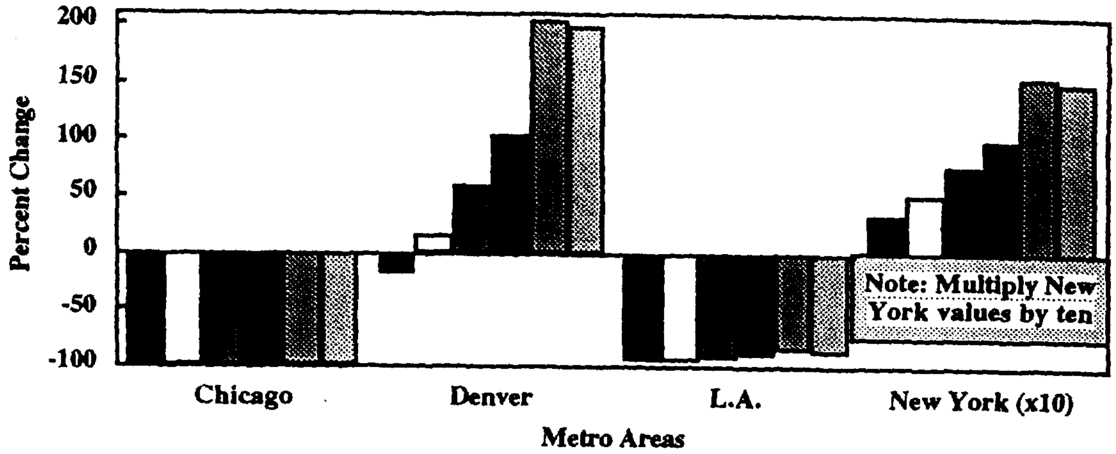


(b) Carbon Monoxide (CO)

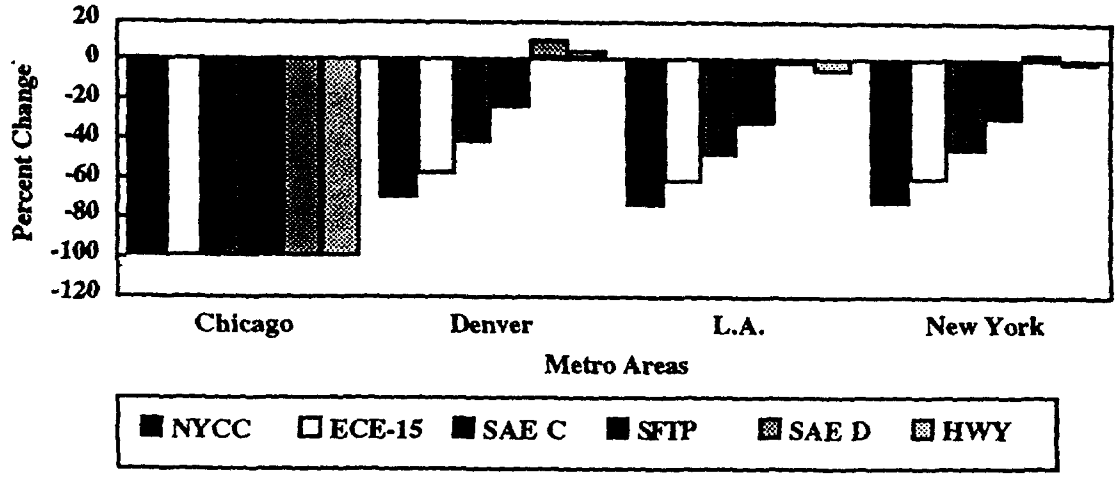


(c) Nitrogen Oxides (NOx)

FIGURE 1. EV PERCENT CHANGE EMISSIONS IMPACTS: MOBILE5 SPEED CORRECTION FACTORS



(d) Sulfur Oxides (SO_X)



(d) Carbon Dioxide (CO_2)

FIGURE 1 (CONT.) EV PERCENT CHANGE EMISSIONS IMPACTS: MOBILE5 SPEED CORRECTION FACTORS